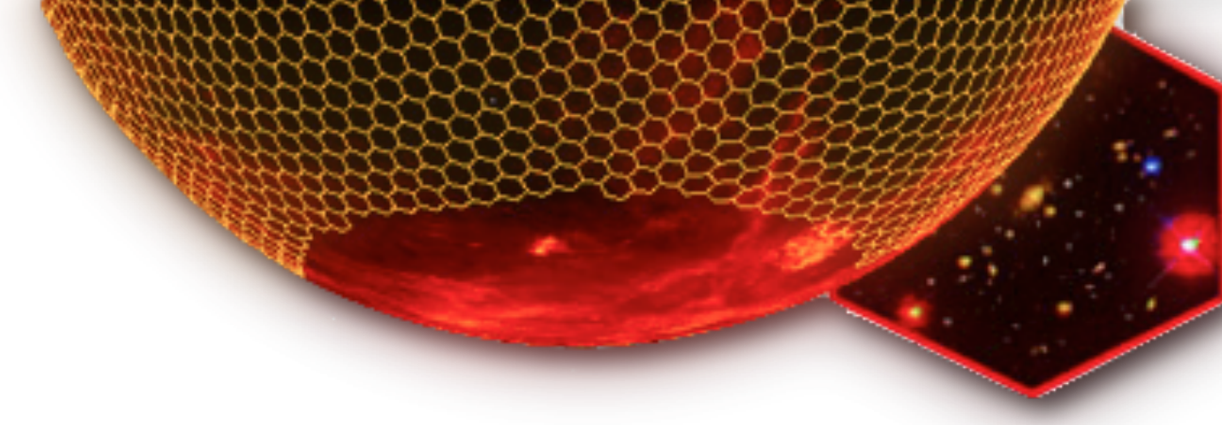

Strong Gravitational Lenses in the Dark Energy Survey

New Lenses and Search Techniques

Brian Nord
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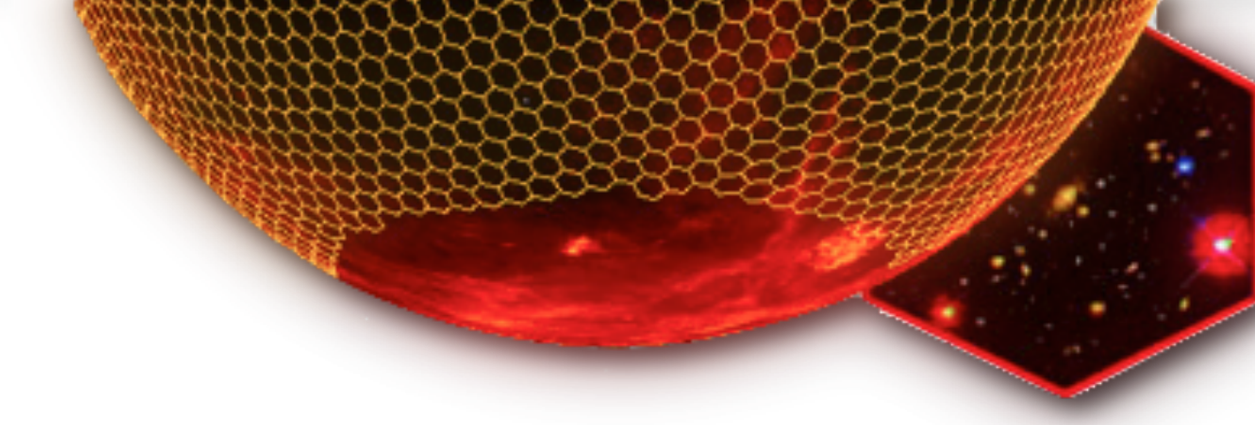
@briandnord

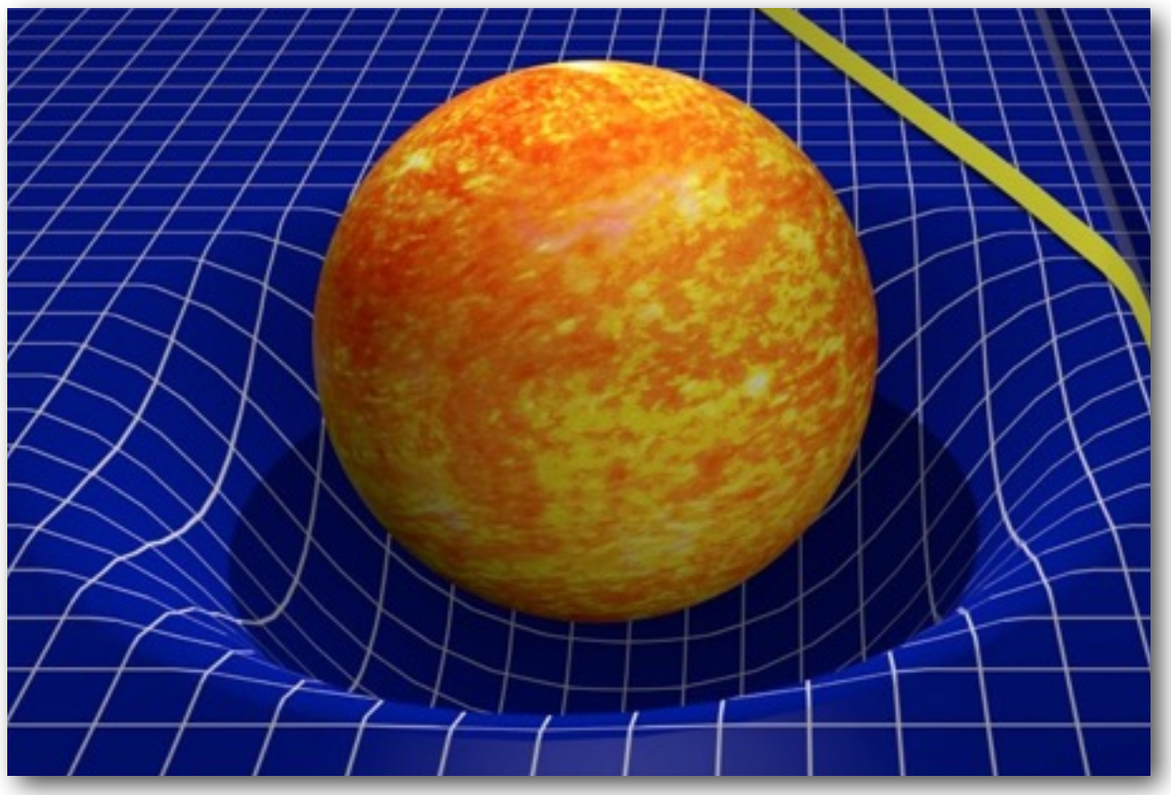
Sneak Preview

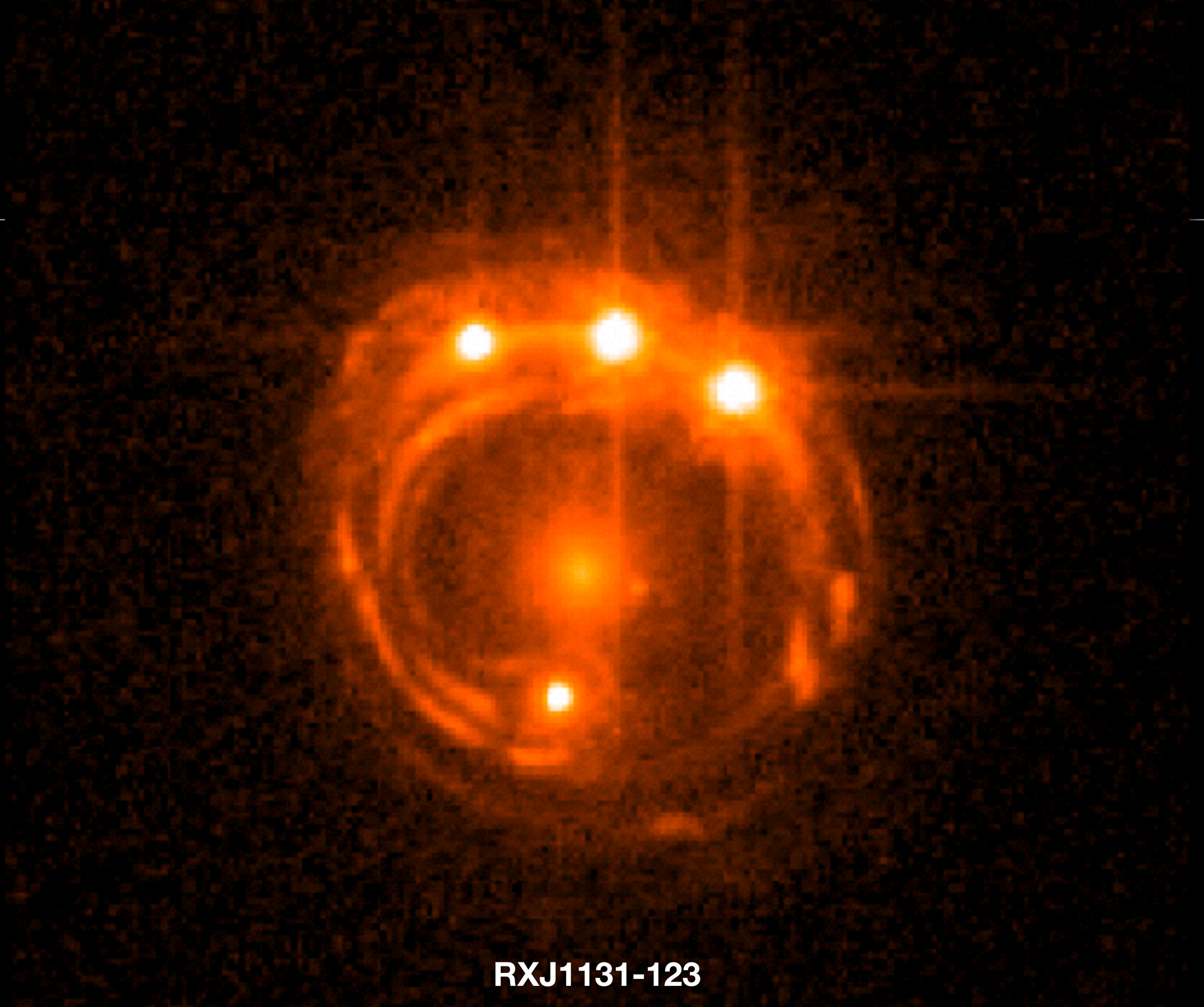
- Strong Gravitational Lensing as a cosmological probe
- How to discover a lens: recent finds in DES
- New techniques for finding lenses



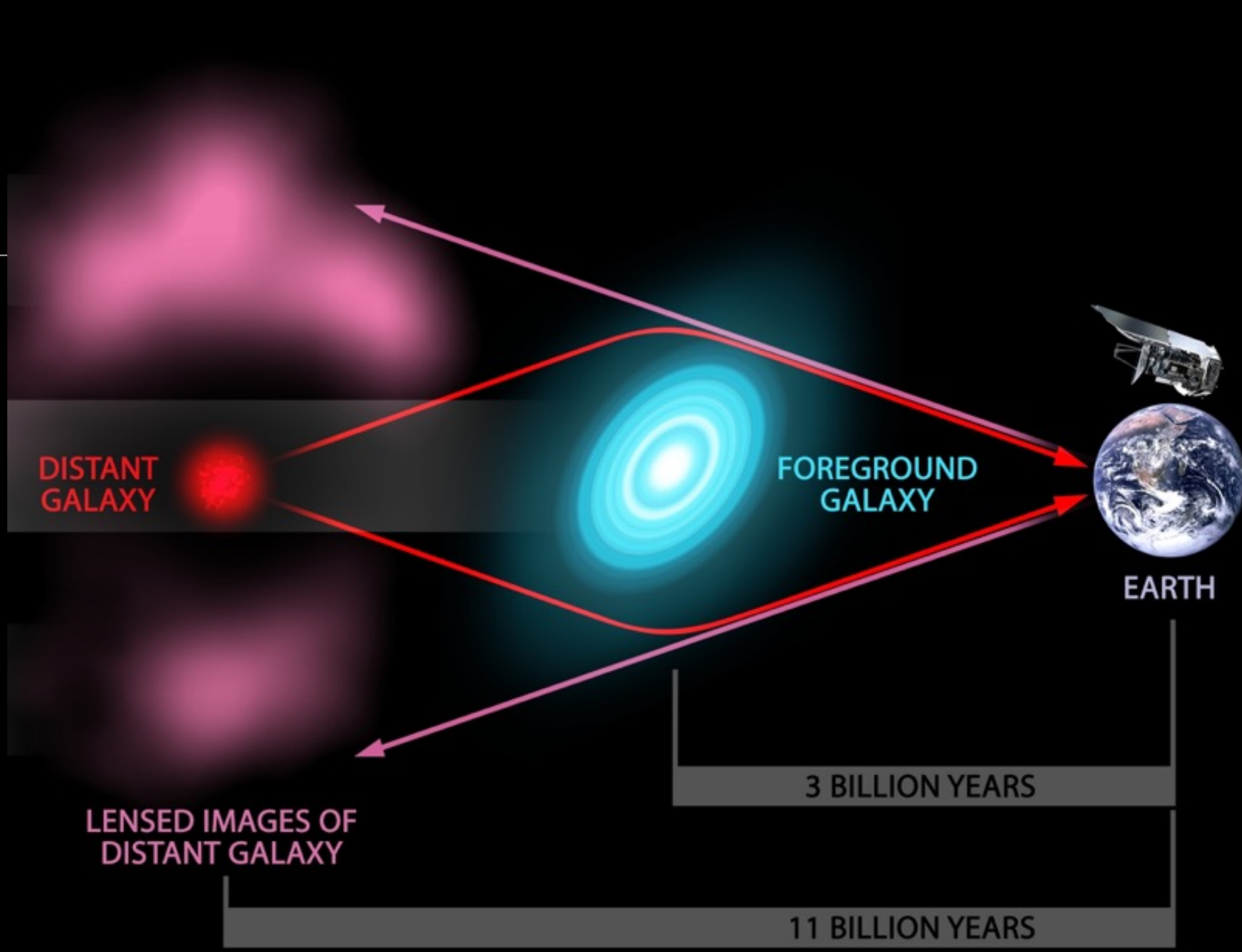
Warped Perspective:
How strong lensing works

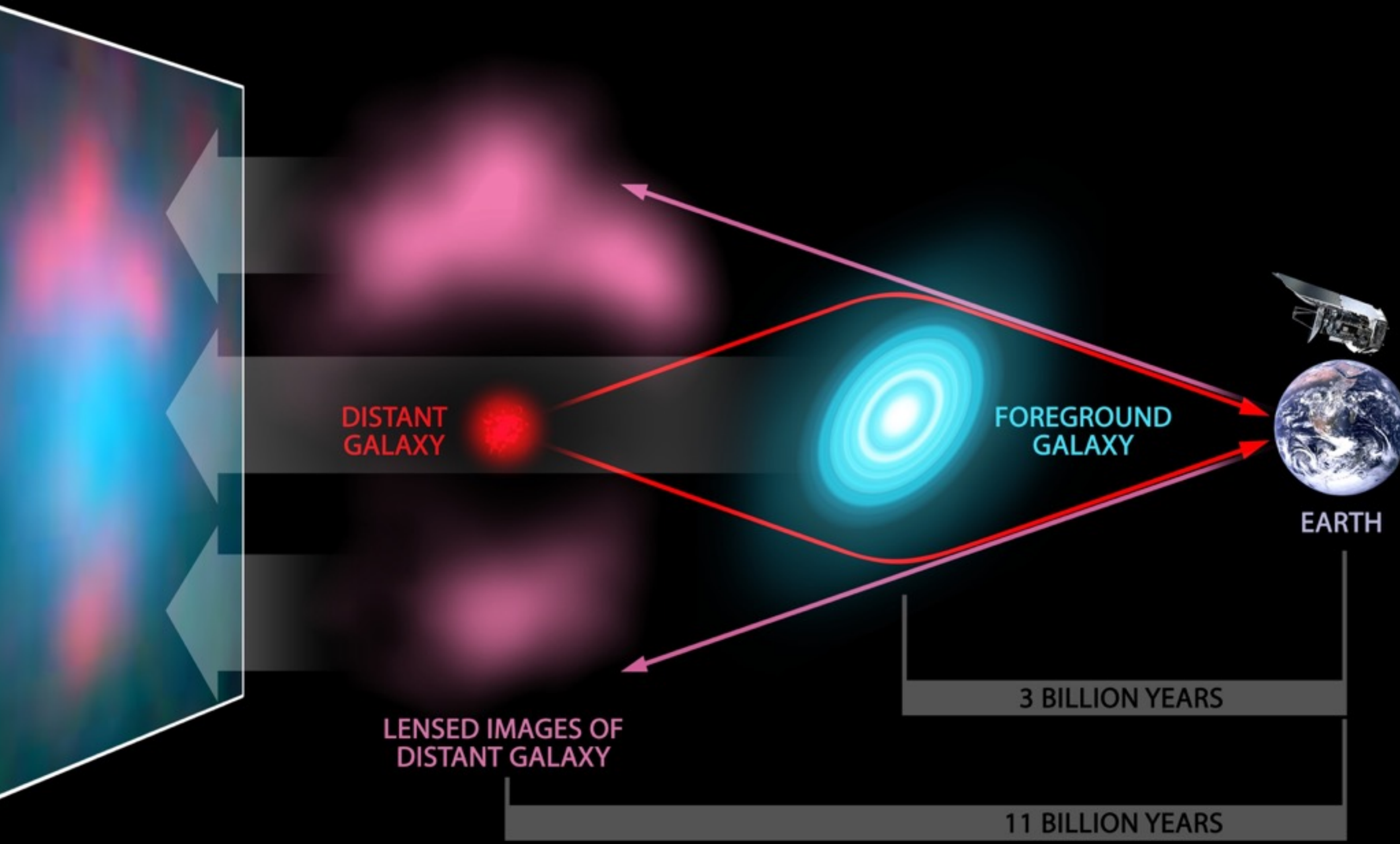
Energy tells space how to curve, and space tells energy how to move.





RXJ1131-123


DISTANT
GALAXY
FOREGROUND
GALAXY
EARTH
3 BILLION YEARS
LENSED IMAGES OF
DISTANT GALAXY
11 BILLION YEARS


DISTANT
GALAXY
FOREGROUND
GALAXY
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LENSED IMAGES OF
DISTANT GALAXY
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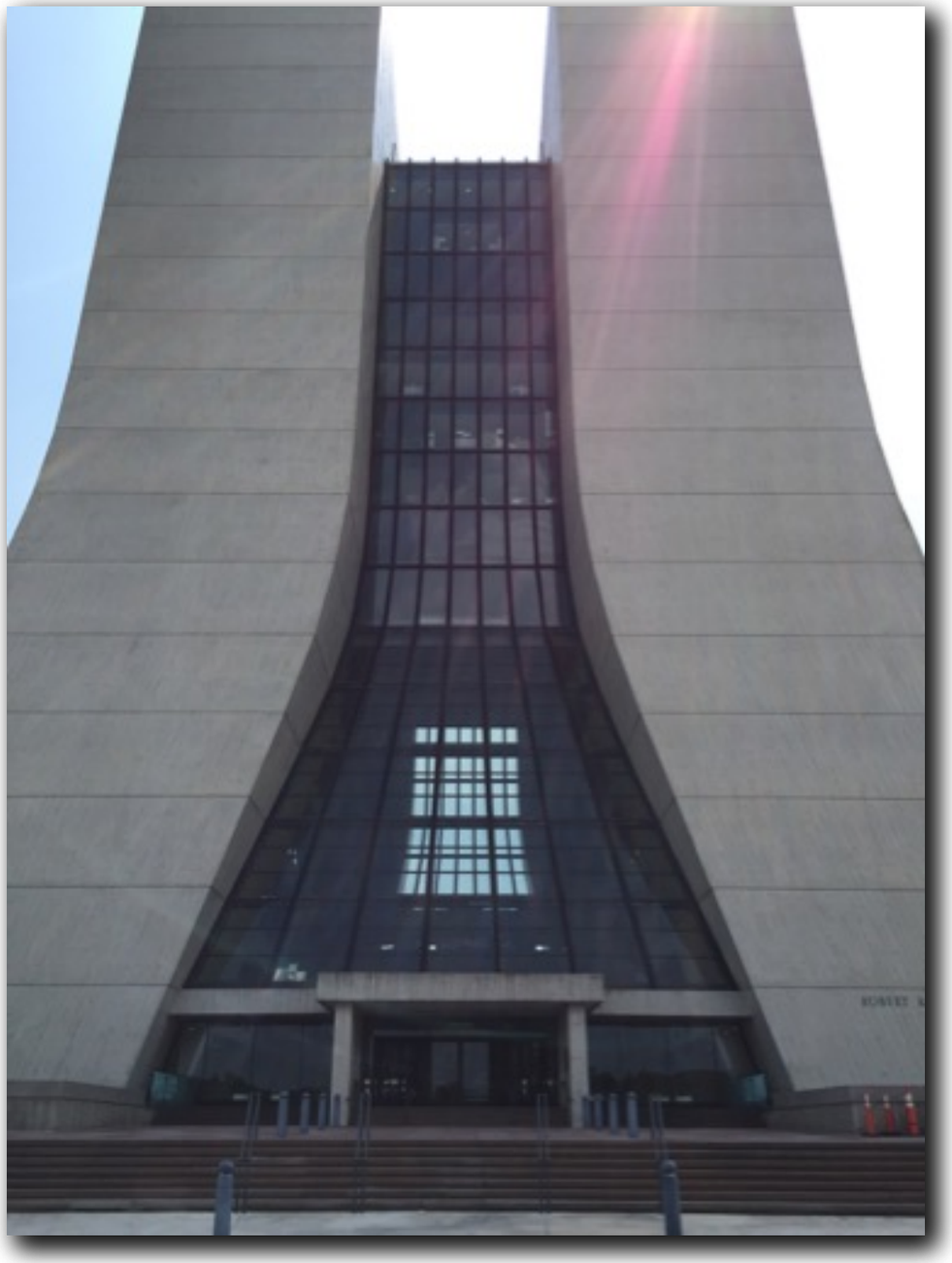
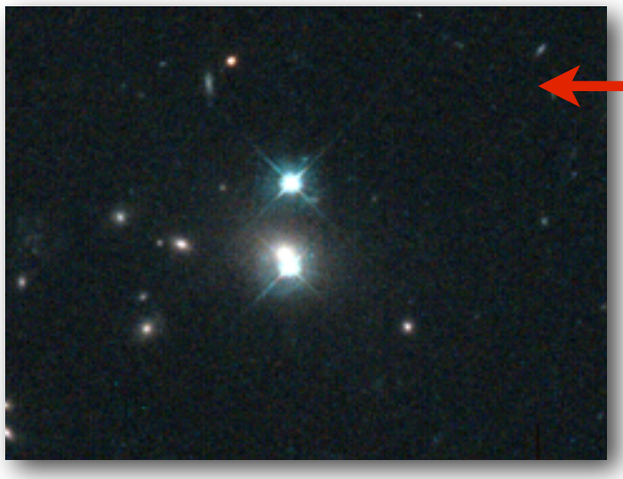
Wilson Hall Lensed

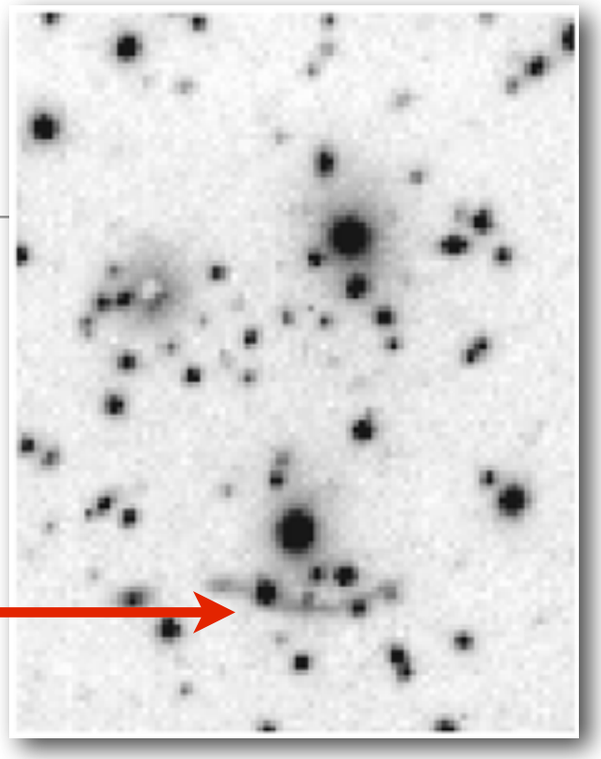


via GravLensHD by Eli Rykoff

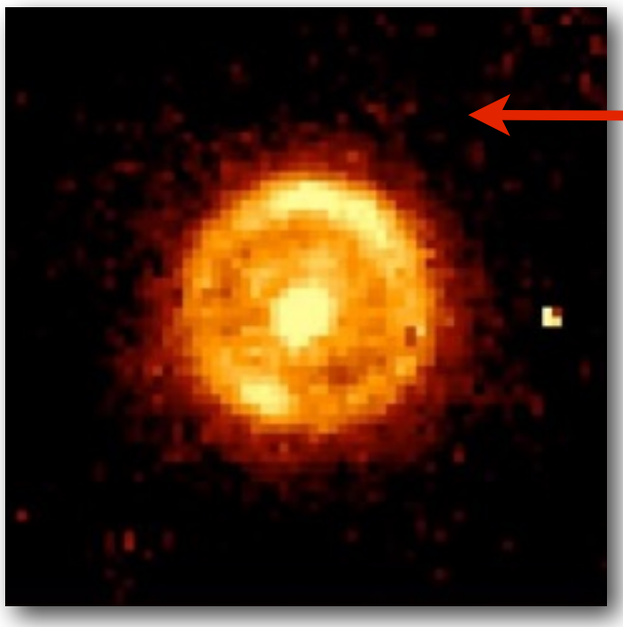
Historical Milestones



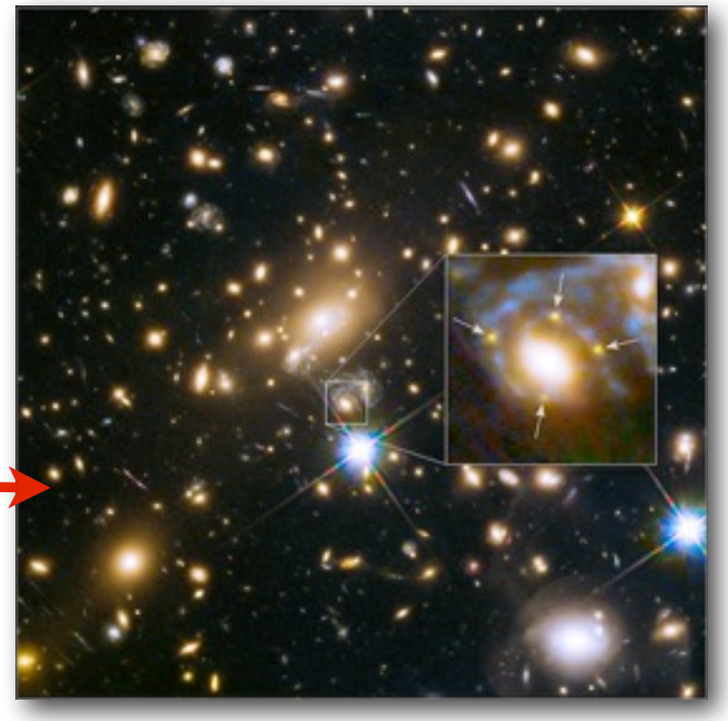
- 1979: First lensed system
  - Twin Quasar SBS 0957+561
    (Walsh, Carswell, Weyman)



- 1986: First lensed galaxy (arcs)
  - Galaxy Cluster Abell 370
    (Lynds & Petrosian 1986; Soucail et al. 1987)



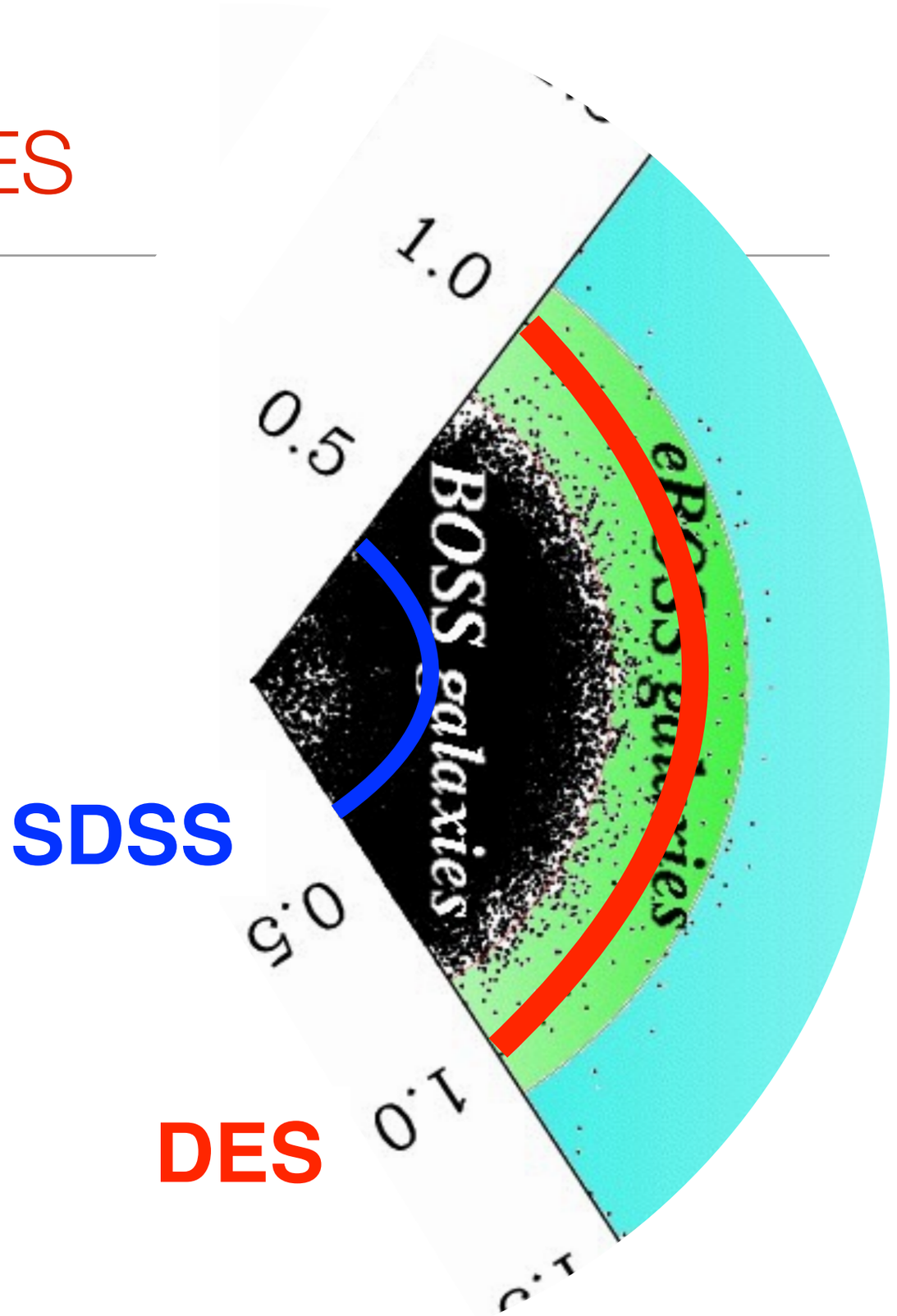
- 1998: First Einstein Ring
  - Galaxy JVAS B1938+666
    (King et al.)



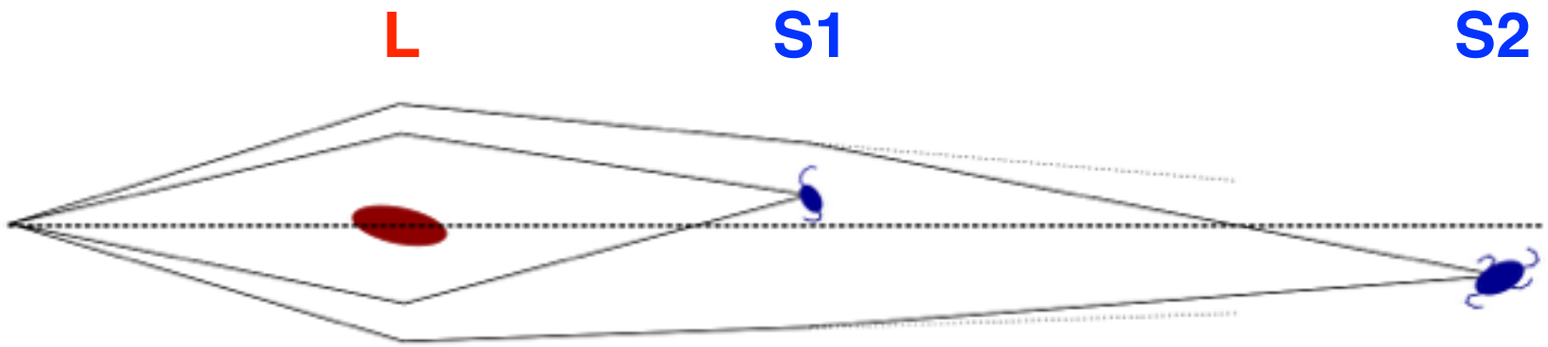
- 2014: First multiply imaged supernovae
  - MACS J1149.6+2223
    (Kelly et al., 2014)

Strong Lens Forecasts for DES

- Census
  - Variety of techniques and wavelengths, from radio to optical.
  - ~1000 strongly lensed systems have been discovered to date.
  - About half of those come from optical searches.
- Current predictions for DES discovery:
  - **~2000 lenses** (galaxy- to cluster-scale)
  - **~120 lensed quasars and < 10 lensed supernovae** (Oguri & Marshall, 2010)
  - made possible by red-sensitive DECam CCDs



Lenses for Cosmology
Double-source systems



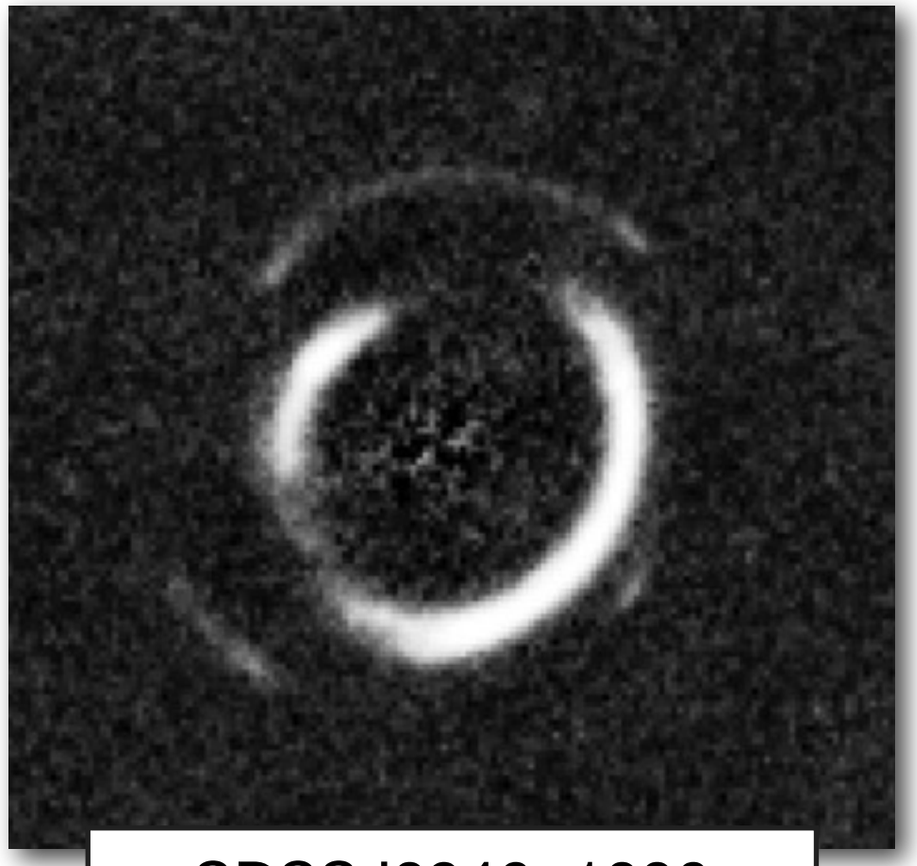
- Distance is a function Hubble parameter and matter and dark energy densities:

$$D_{ij}(\, z_L,\, z_s\, ;\, H_0,\, \Omega_M,\, \Omega_\Lambda,\, w\,)$$

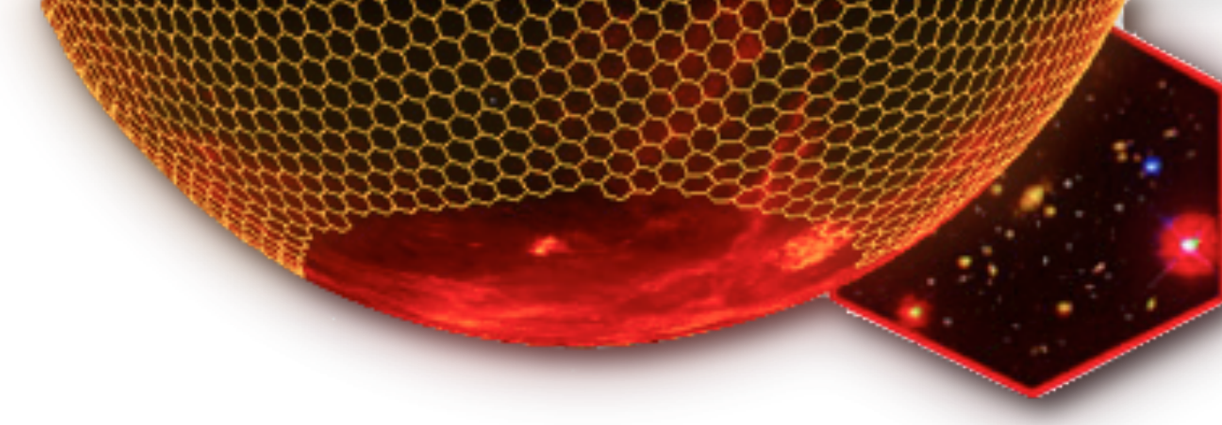
- The ratio of distances, ***D***, provides constraints $\boldsymbol{\Omega_M}$, $\boldsymbol{\Omega_\Lambda}$, $\boldsymbol{w}$ independent of H_0

$$\Xi(z_{\rm lens}, z_1, z_2; \Omega_M, \Omega_\Lambda, w) = \frac{D_{\rm LS}(z_1)}{D_{\rm S}(z_1)} \frac{D_{\rm S}(z_2)}{D_{\rm LS}(z_2)}$$

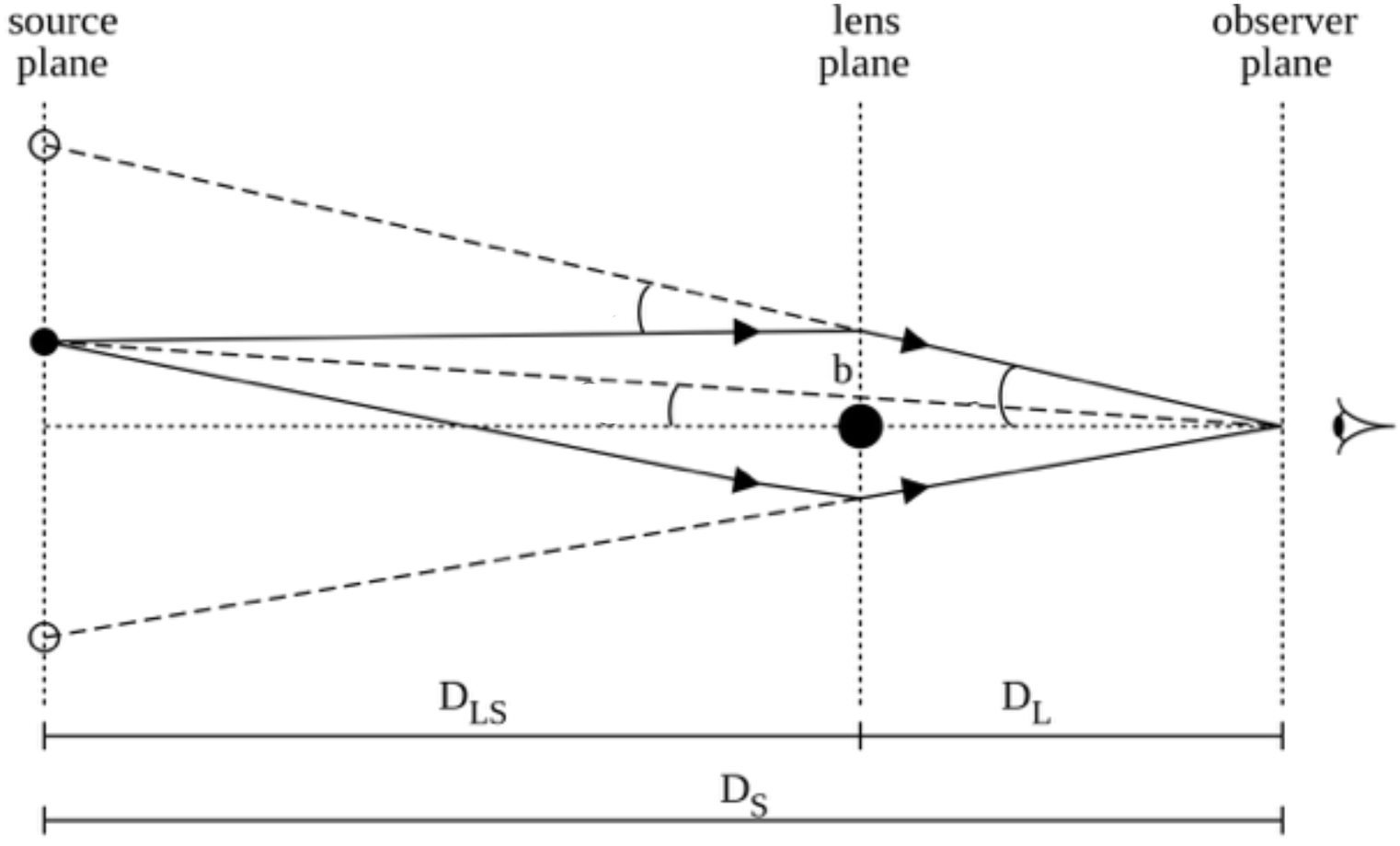
- To date, only one has been found.
- We expect ~10 in DES (Gavazzi++2008)



SDSSJ0946+1006



How to find a strong lens



DES at a Glance:
Survey Footprint

- Total area: 5000 sq. deg.
- Science Verification: ~200 sq. deg.
- Supernova fields: 2 deep + 8 shallow

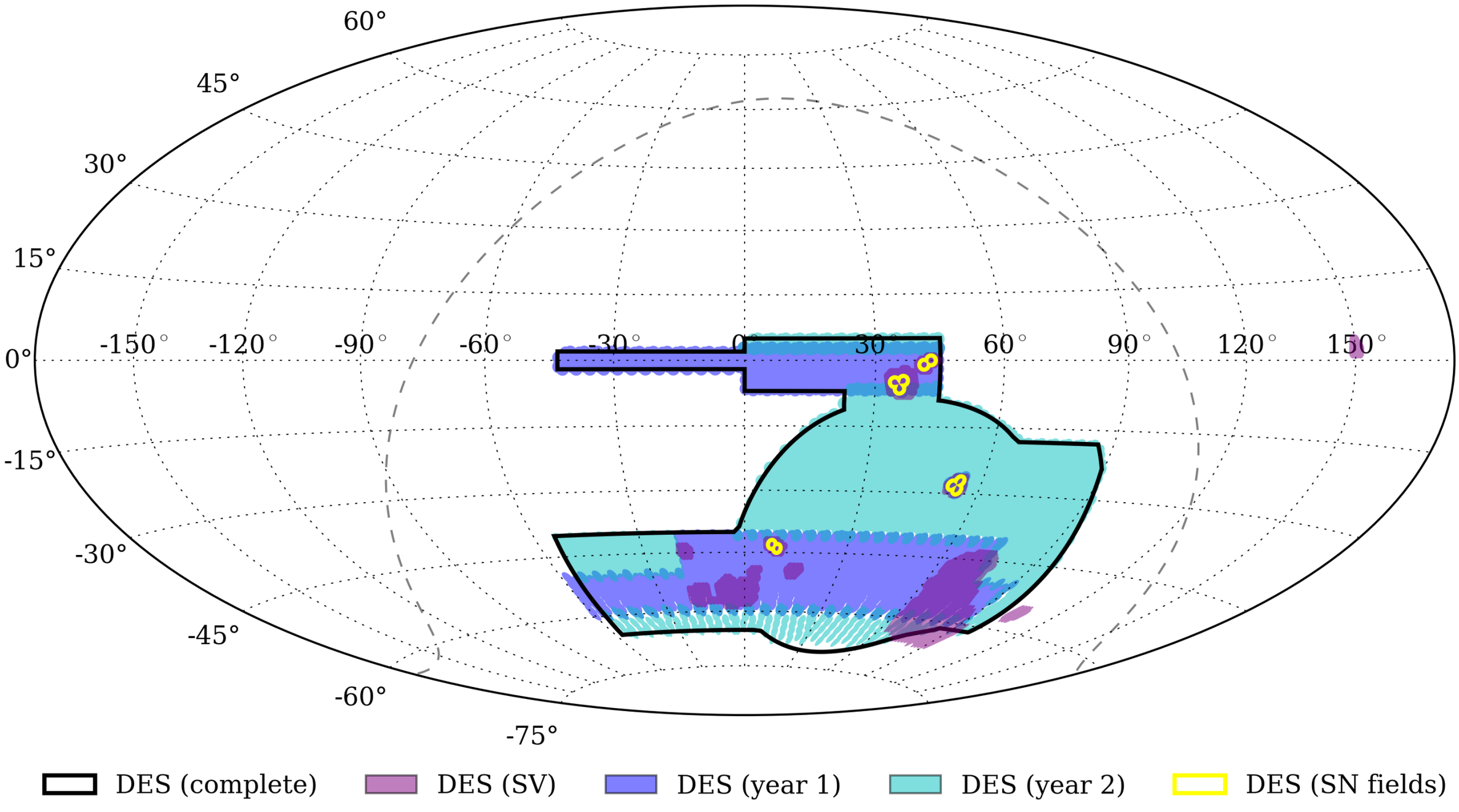
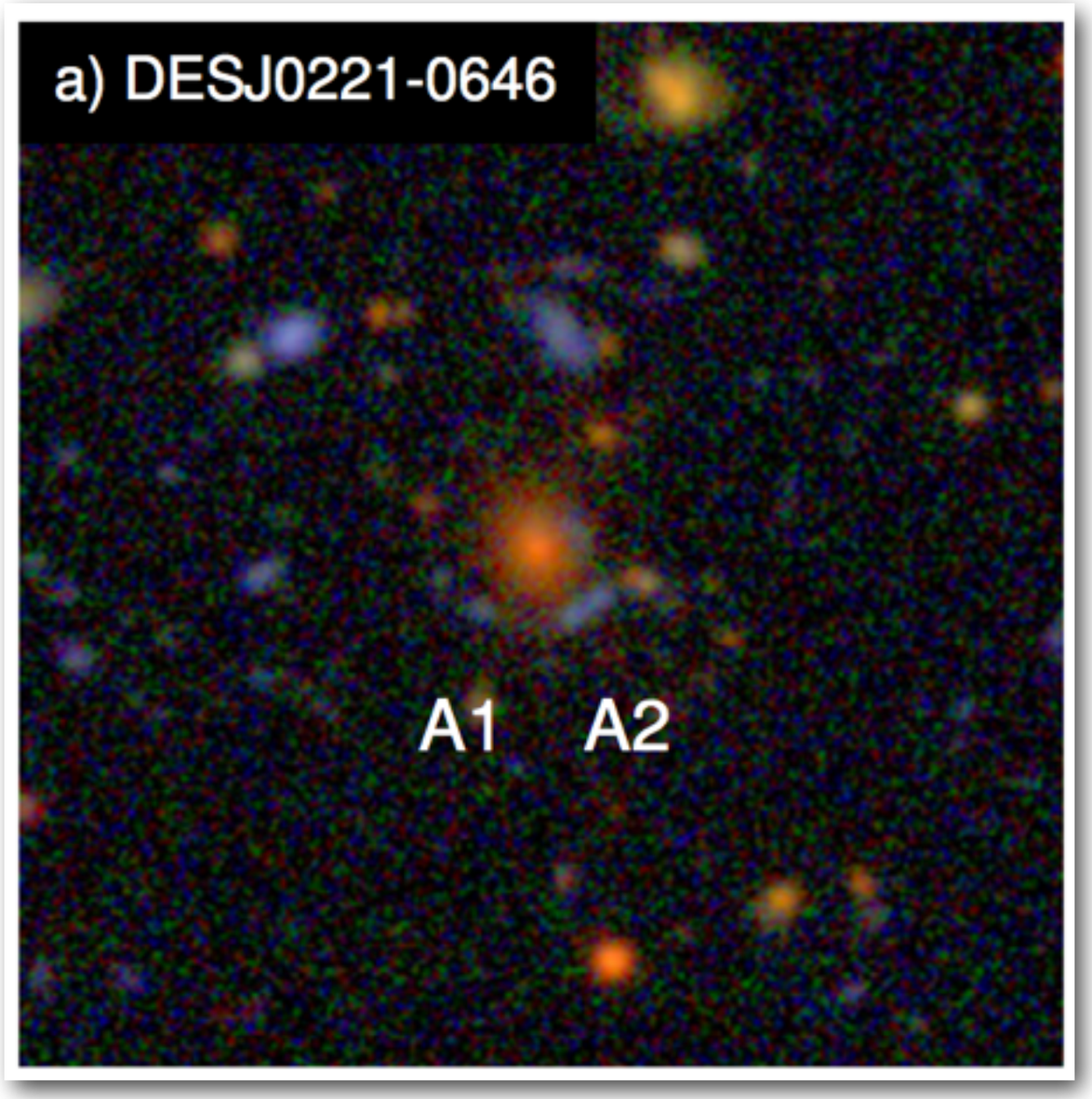


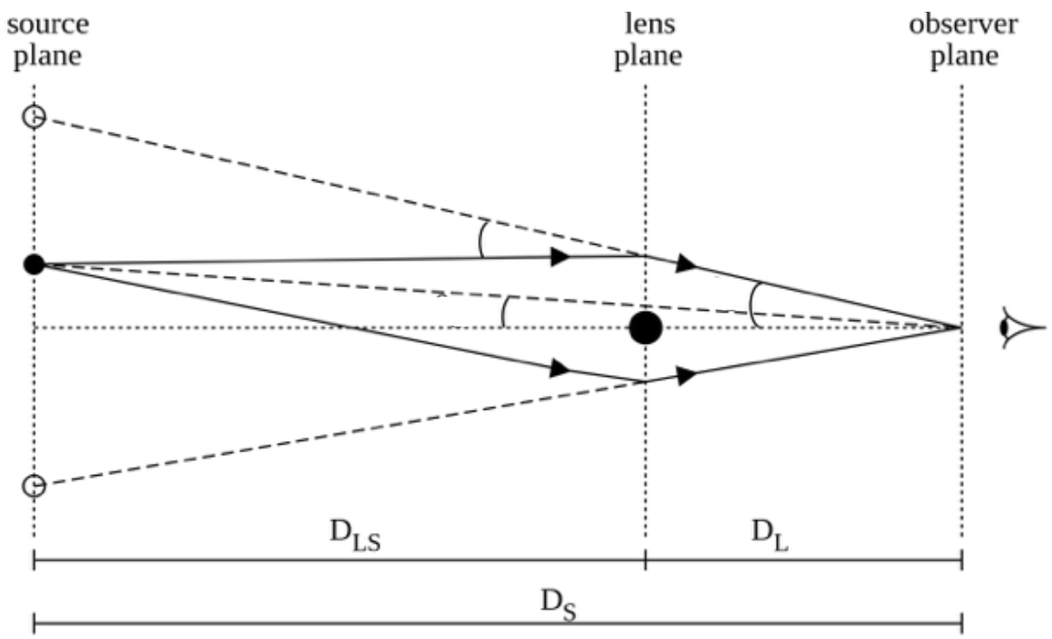
Image Searches

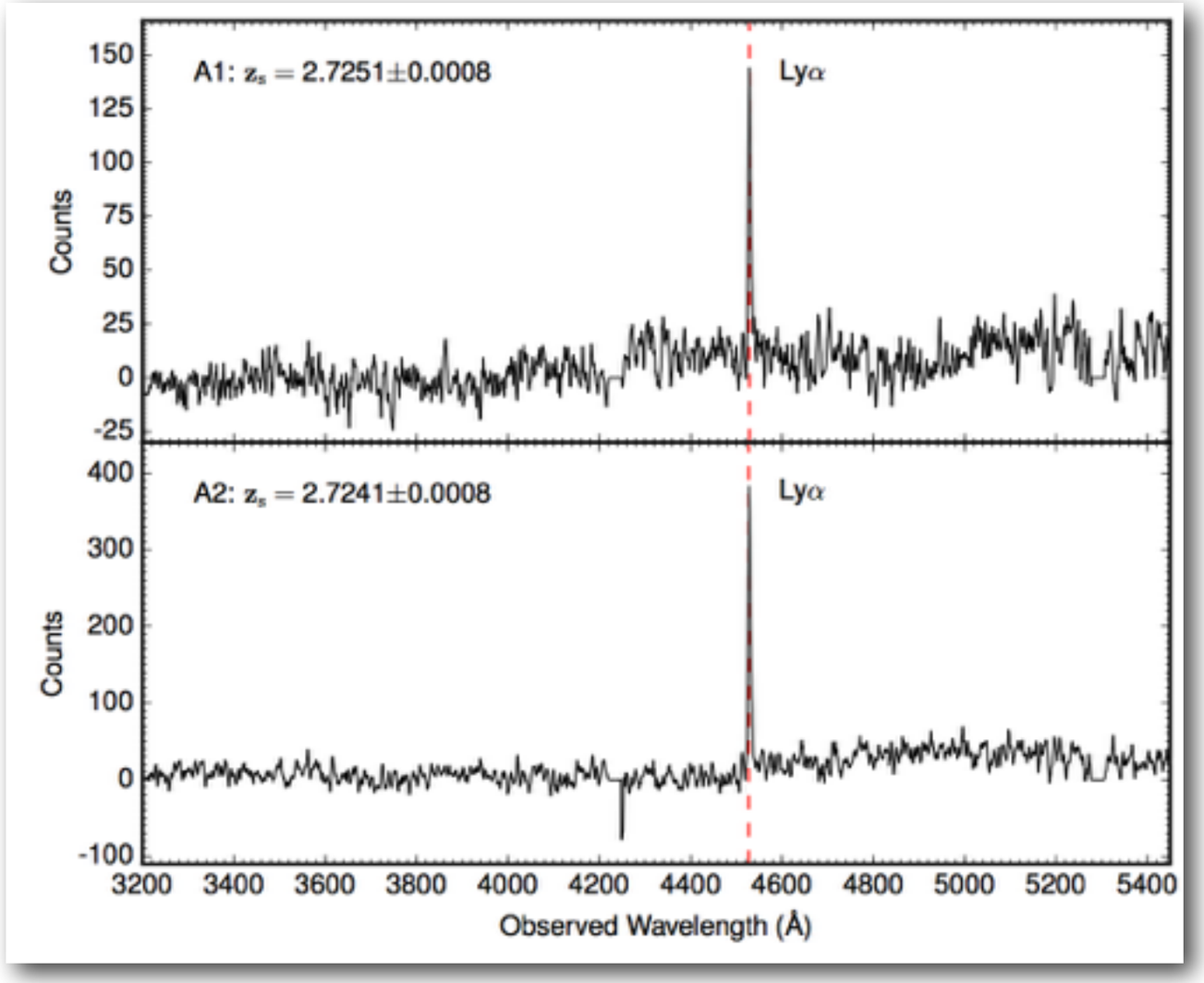
- Search images for lensing features
  - Identify morphological and photometric features that imply a lensing configuration.
  - Blue sources near red lenses is a good example; distant star-forming galaxies lensed by nearer dead elliptical galaxies
- Search Methods:
  - visual scanning still always required
  - algorithms can narrow down the search, but they typically produce incomplete or impure samples



Confirm Positions

- Obtain spectra to measure redsfhits and angular diameter distances
  - Patterns in spectral features determine spectroscopic redshift (similar to photo-z)
  - Determine whether the source is farther away than the lens.
  - errors: <1%

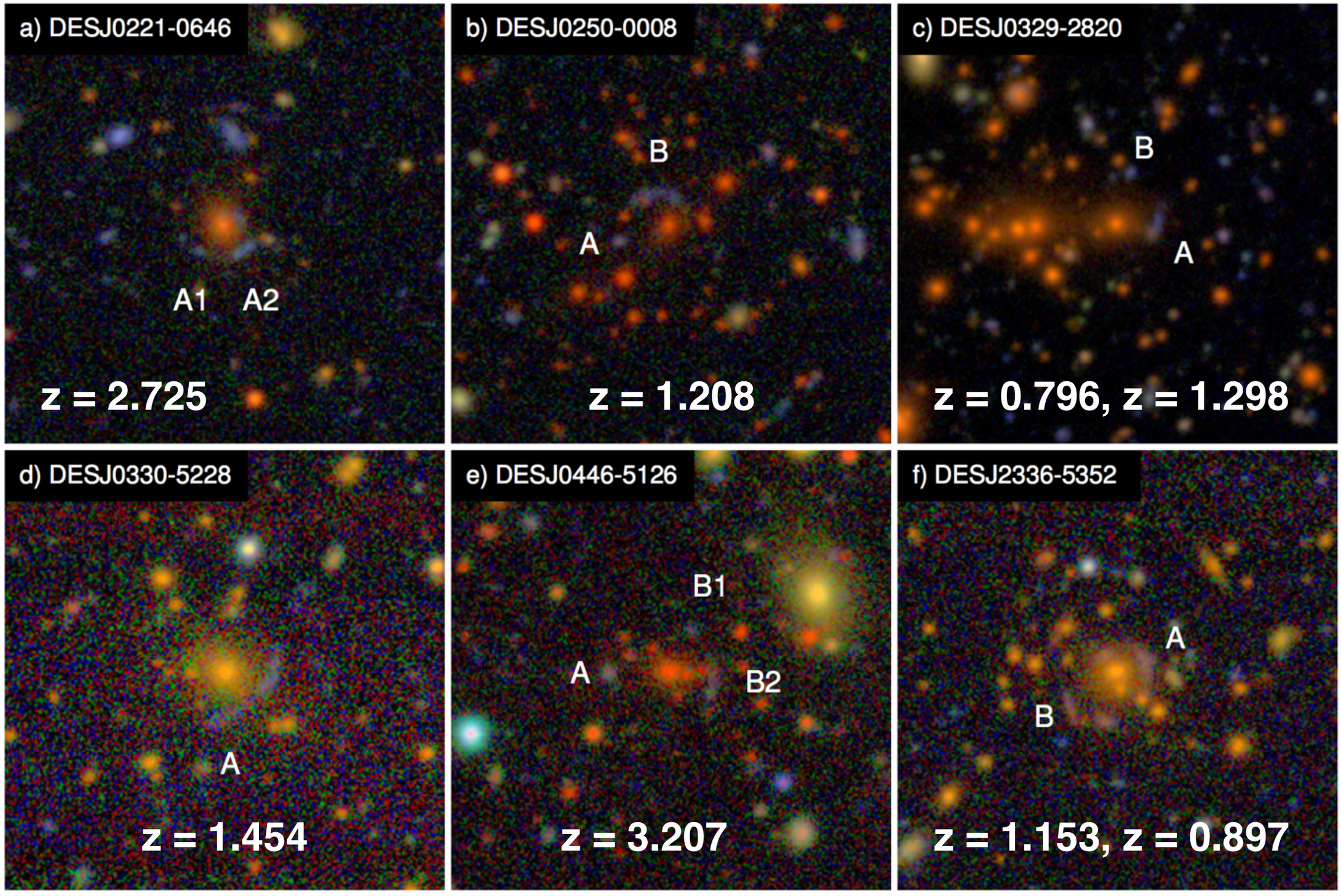




Confirming 6 systems took > 10 hours on Gemini 8m telescope. There isn't yet enough telescope time in the world to follow-up and confirm 1000's of lenses.

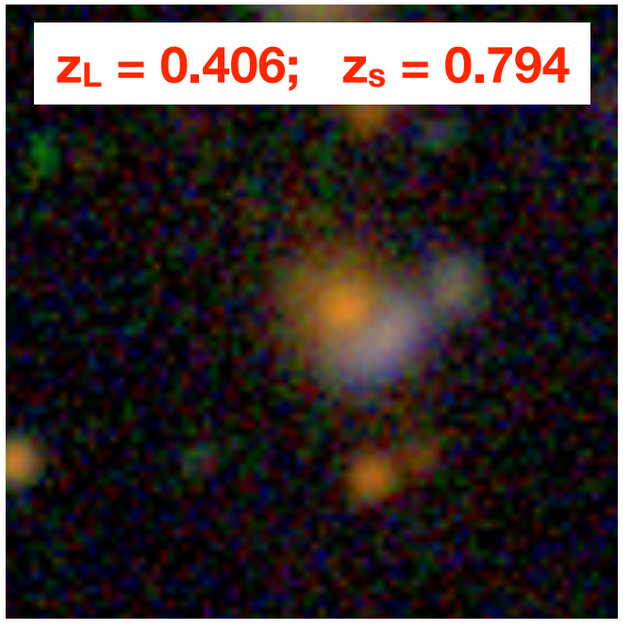
Six Confirmed Lensing Systems in DES SV

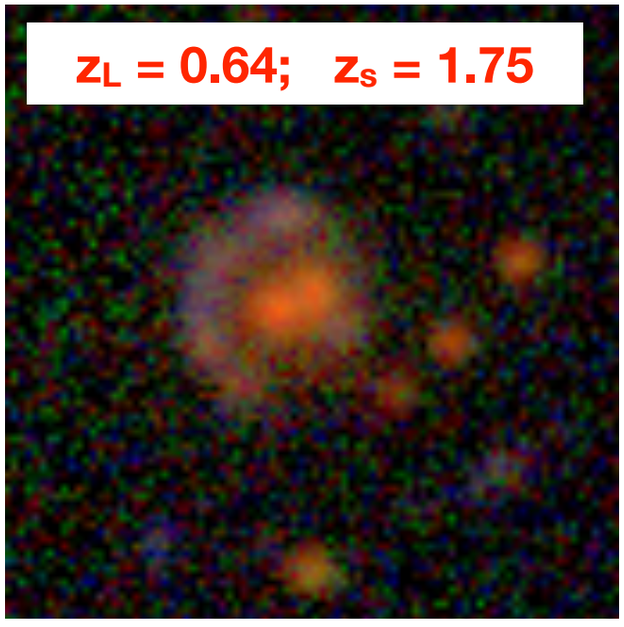
Nord+2015 (arXiv:1512.03062)

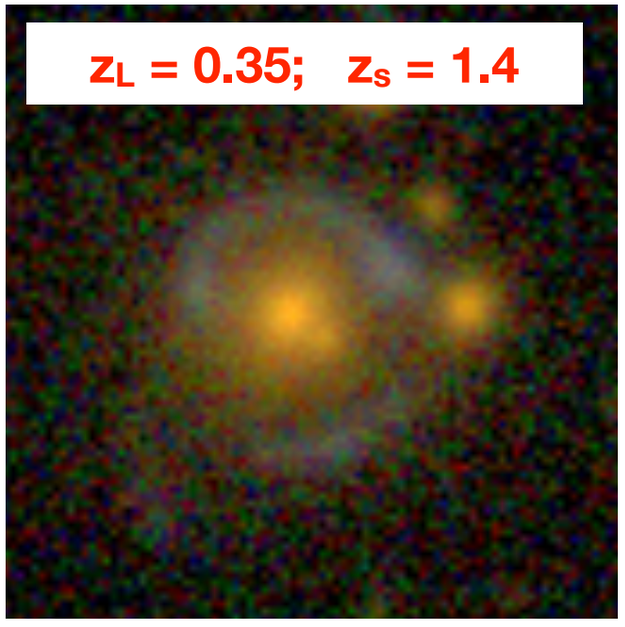


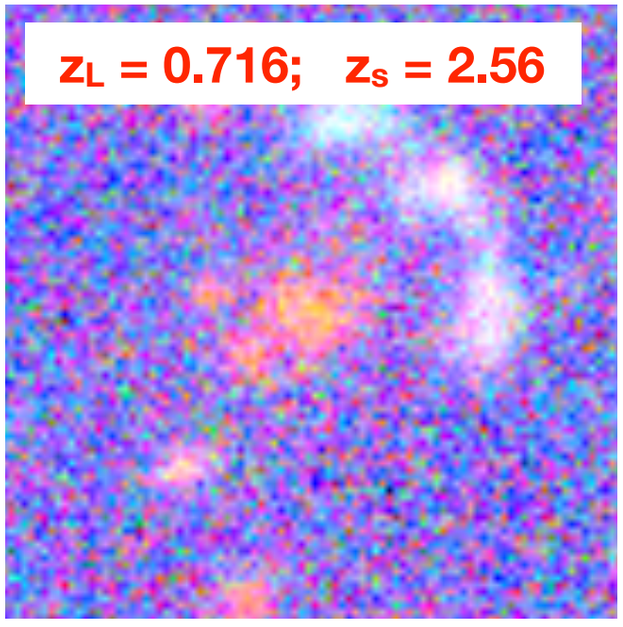
Seven Confirmed Systems in DES Y1

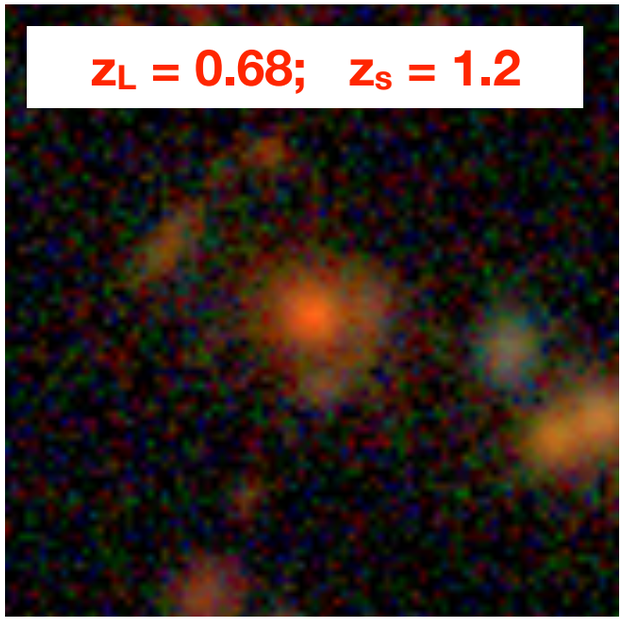
Nord++,2016 (in prep.)

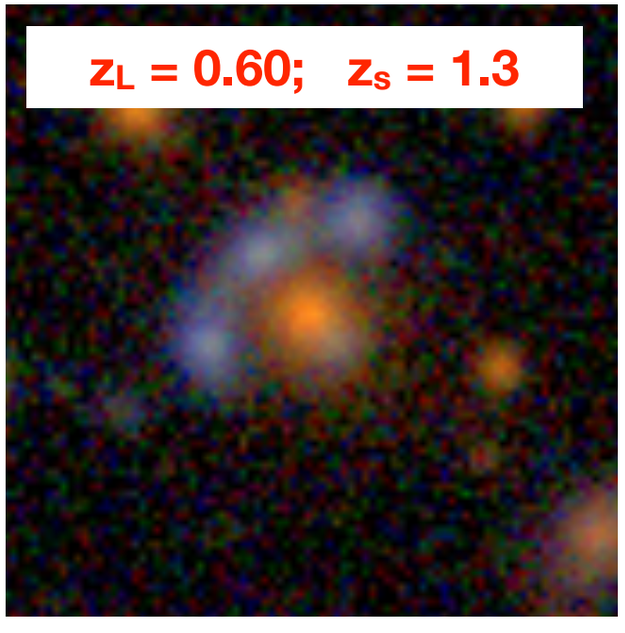












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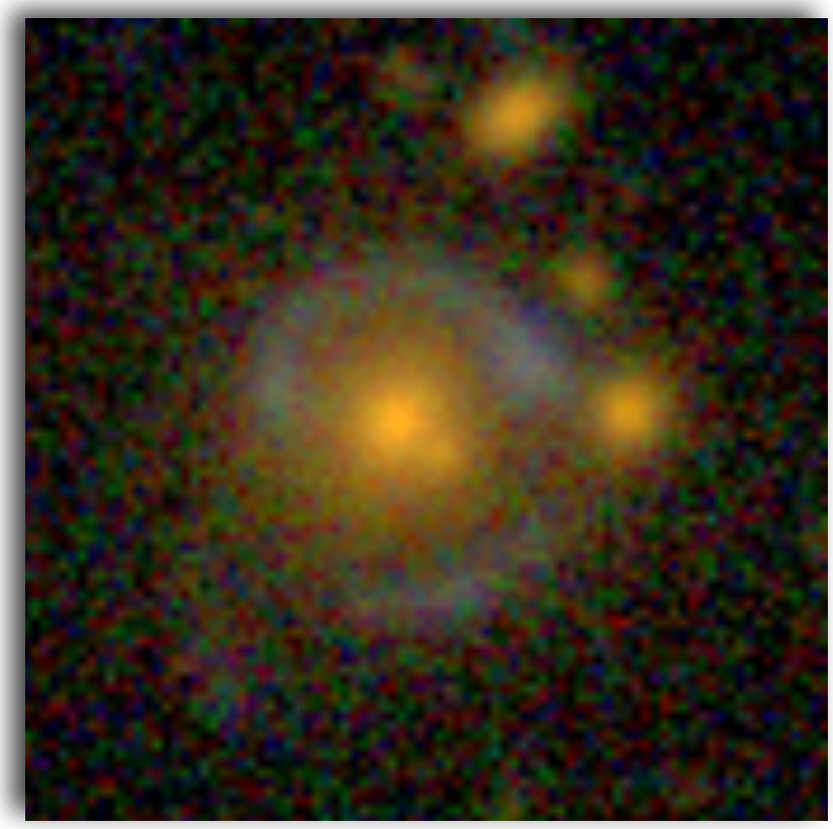
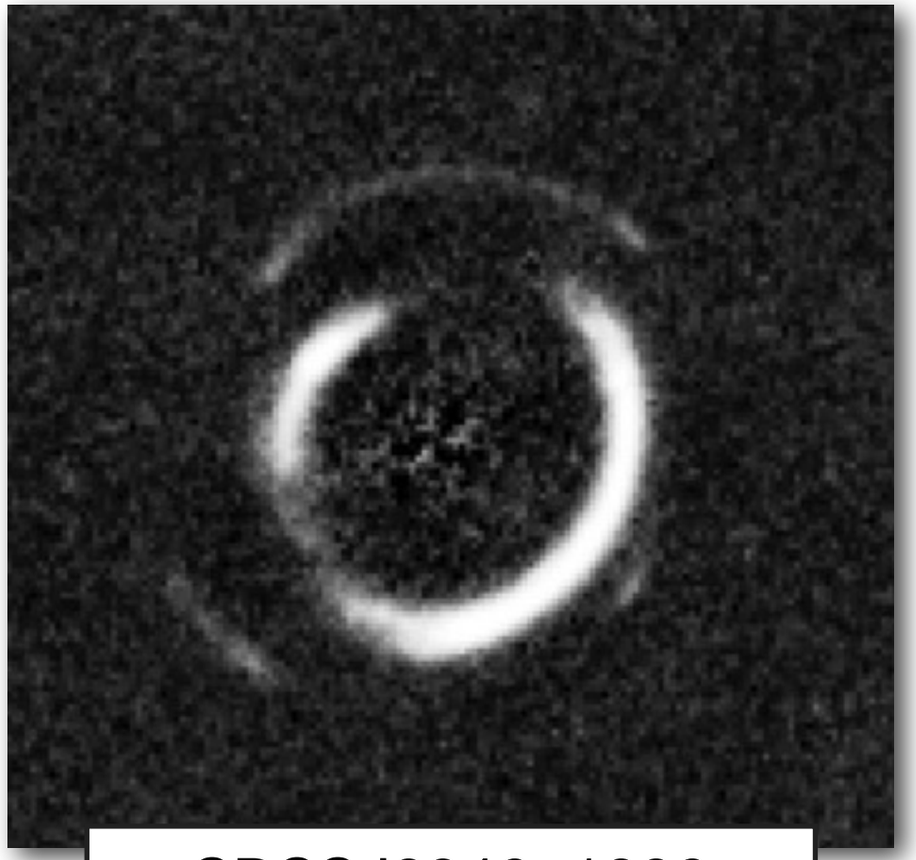
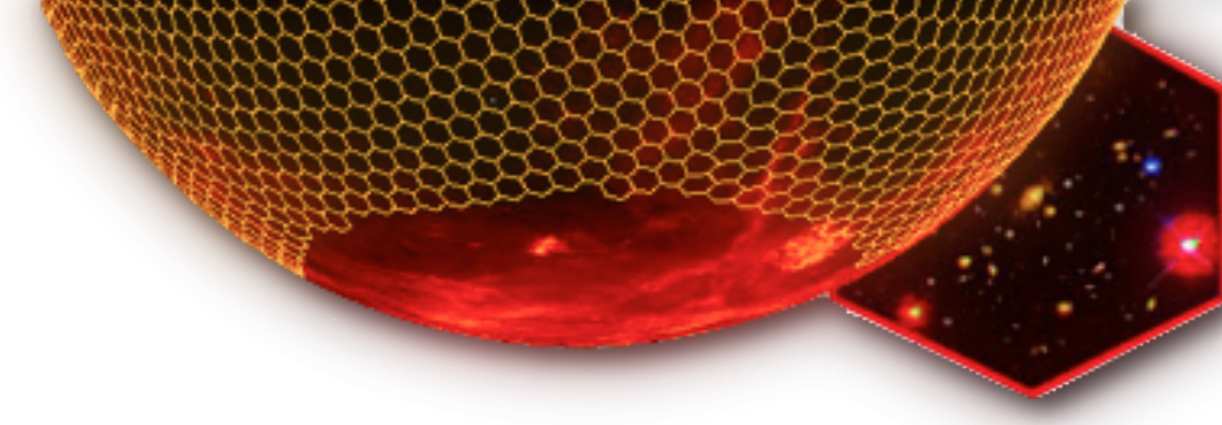




SDSSJ0946+1006

Looking for a specific needle in a stack of needles



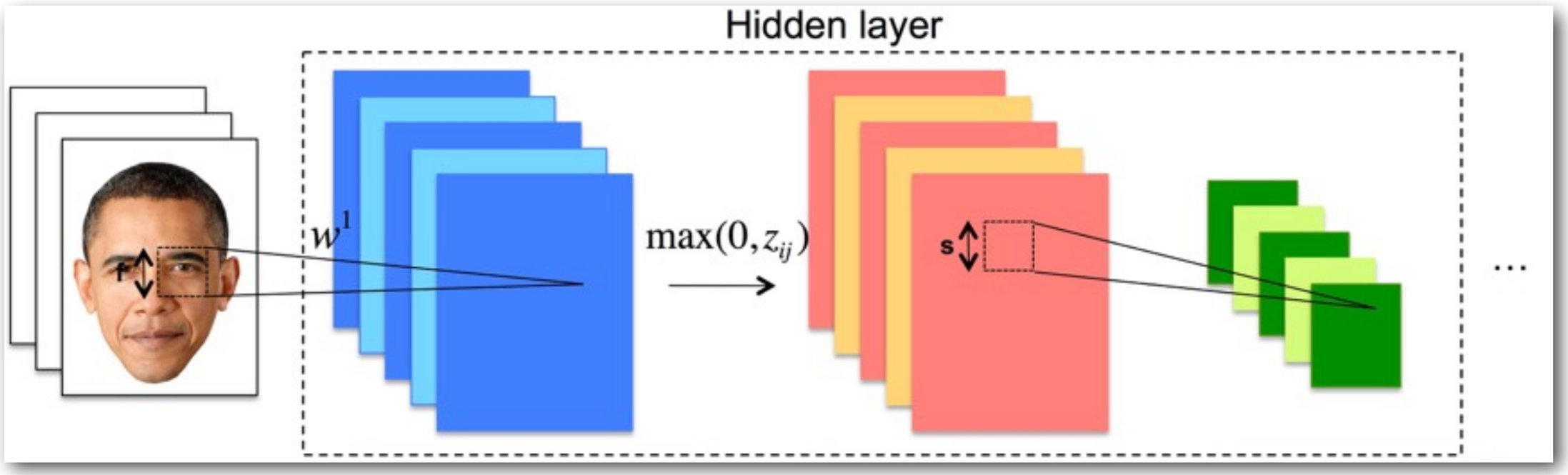
DeepLensing:

Deep Learning techniques for finding lenses

with Irshad Mohammed (Fermilab)

Convolutional Neural Nets
Training: Step-by-Step

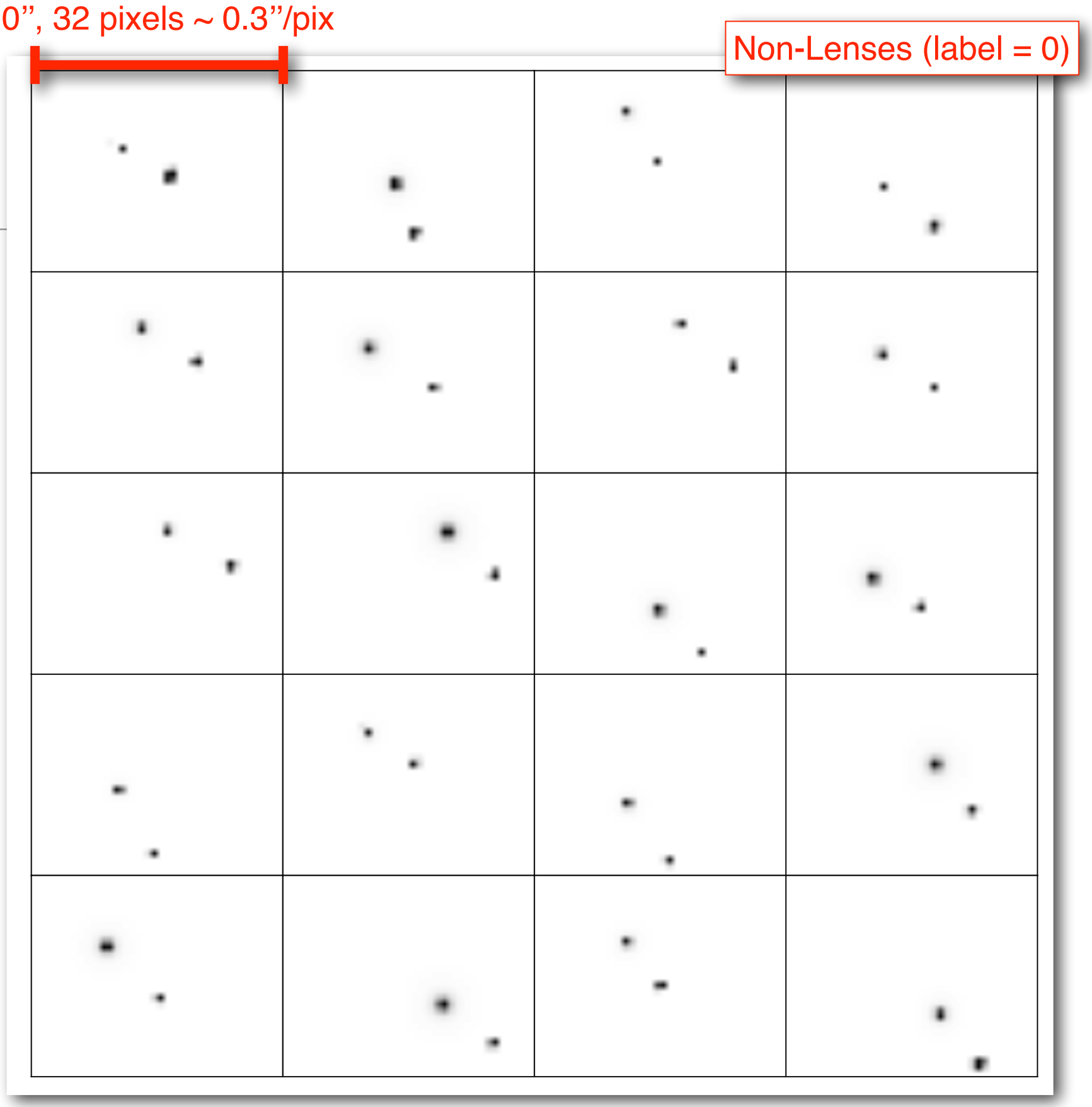
image borrowed from
Christof Angermueller,
Oxford



- Steps
  - *Input*
    training image
  - *Convolution*:
    convolve with parametrized filter
  - *Activation:*
    non-linear function that “activates features”
  - *Feature Map*:
    highlighted features
  - *Pooling:*
    pull out sections of feature map that are most useful
  - *Back-propagation:*
    information fed back to filter parameters
  - *Repeat*:
    each cycle through this process is an “epoch”

DeepLensing Training Sets

- Image characteristics:
  - one band only
  - no noise
  - *32x32 pixels (10”x10”)*
- Lens Systems
  - single lens and single background source



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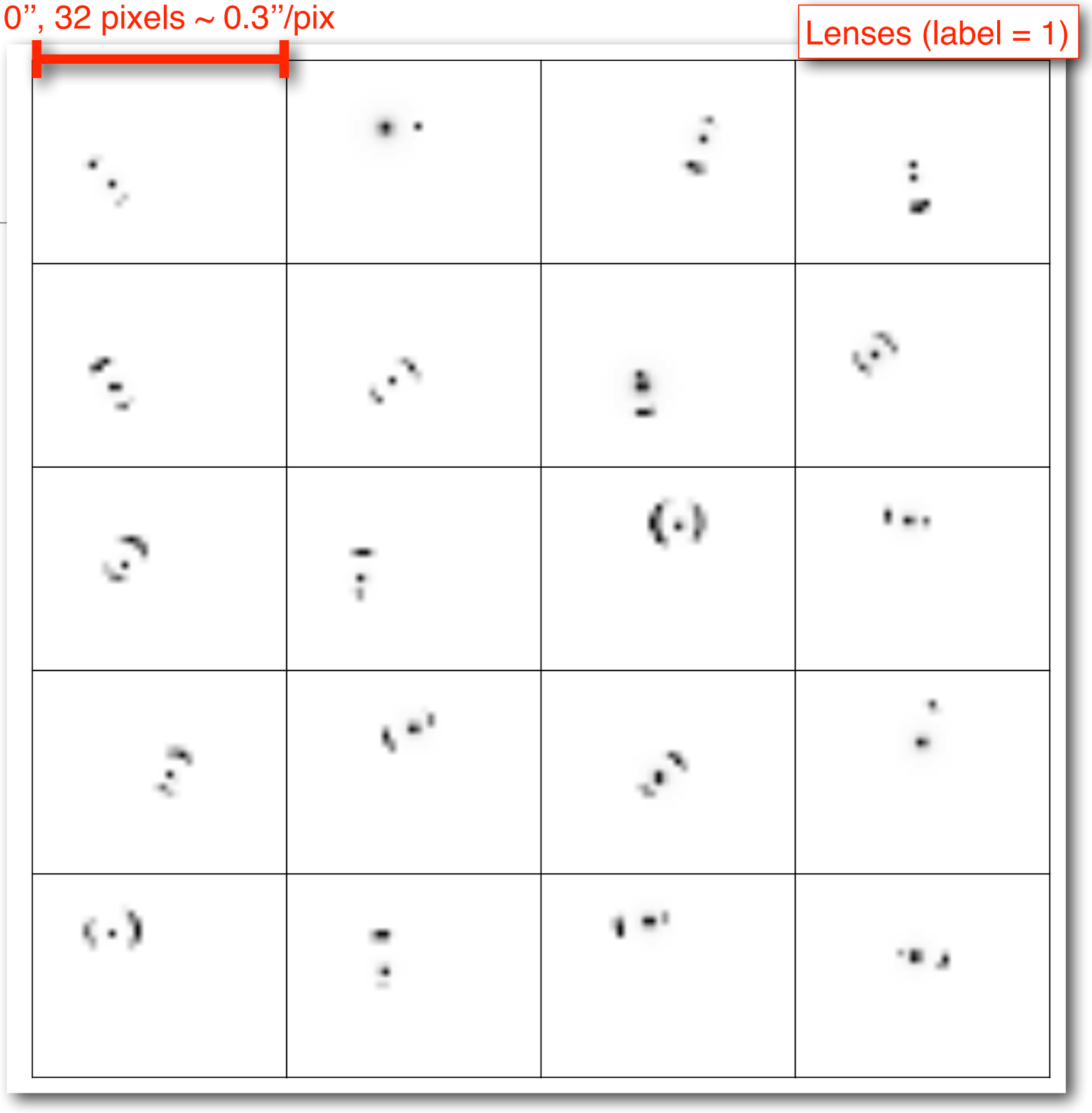
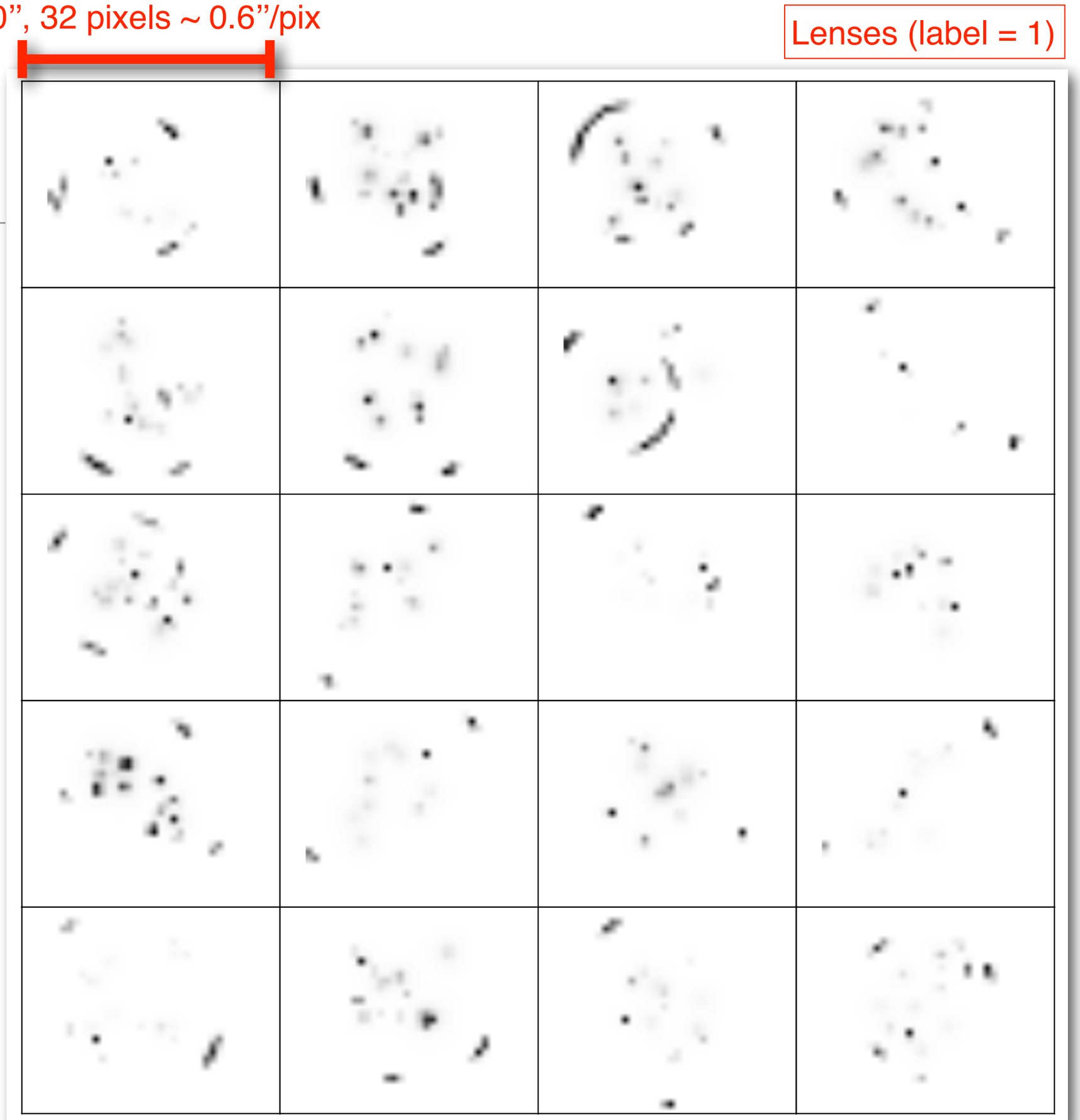


DeepLensing Training Sets

- <u>Image characteristics:</u>
  - one band only
  - no noise
  - *32x32 pixels (20”x20”)*
- <u>Lens Systems</u>
  - multiple lenses and background sources

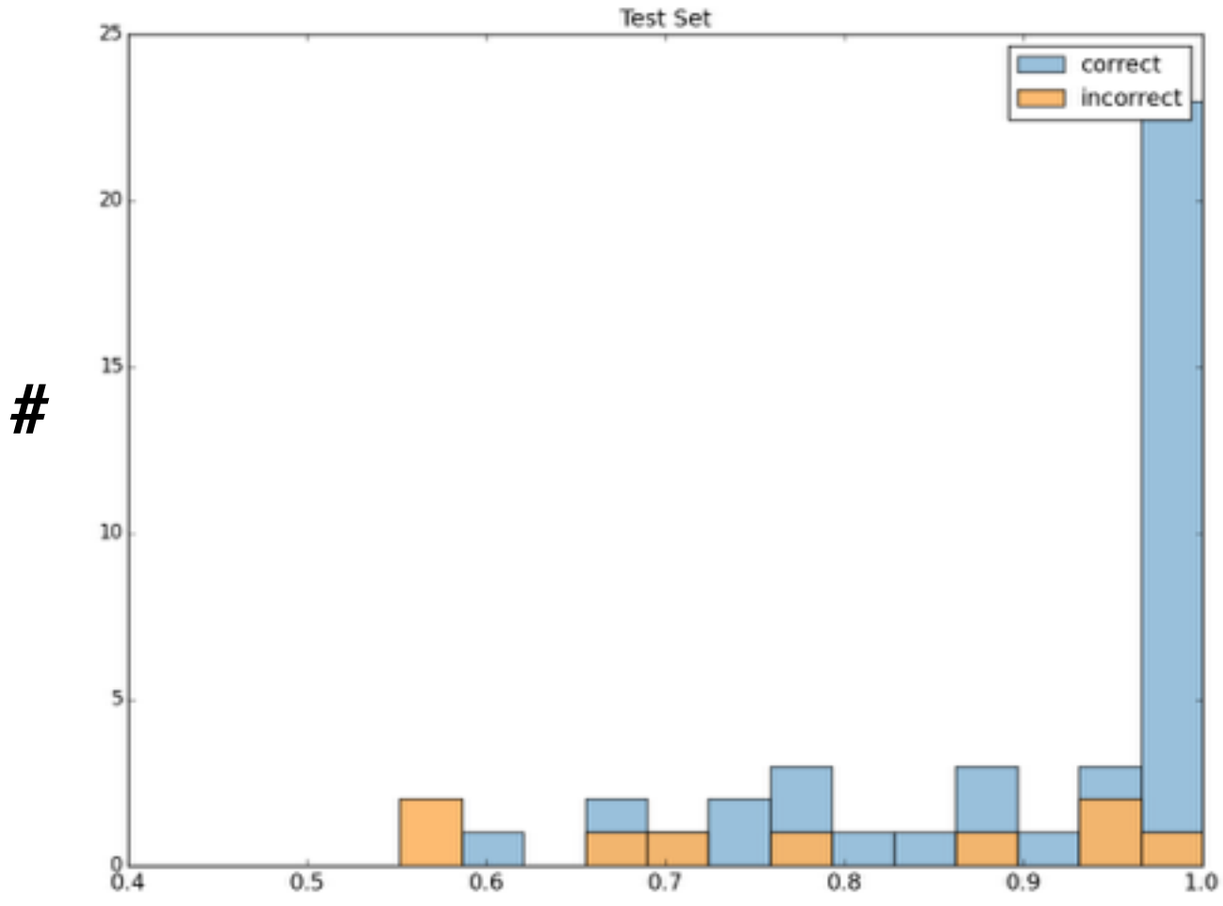
DeepLensing Training Sets

- <u>Image characteristics:</u>
  - one band only
  - no noise
  - *32x32 pixels (20”x20”)*
- <u>Lens Systems</u>
  - multiple lenses and background sources



Preliminary Analysis

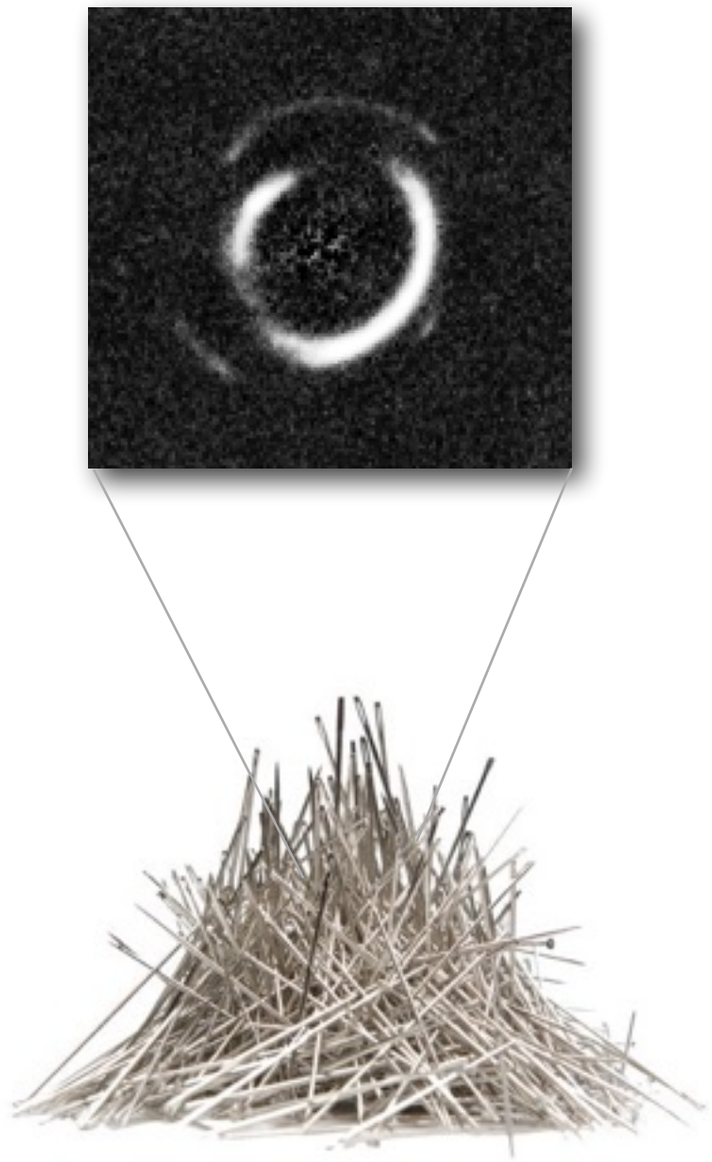
- Training set size:
  3000 total (half with and and without lenses)
- Test set size:
  50
- Epochs (cycles through neural net):
  15
- Total execution time (NVIDIA 750m GPU)
  < 10 min
- No data augmentation (additional translations or rotations of training images)

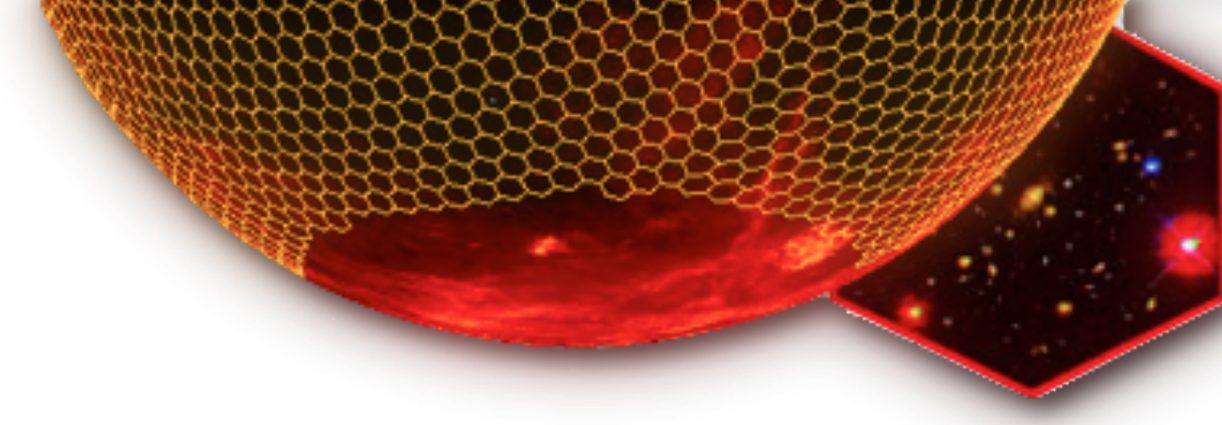


- **95% correct** classification rate
- Patterns in mis-classification are not yet clear.
- Caveats: simulated, clean data for both training and measurement.

DES Strong Lensing

- **DES will find 2x lenses as all previously discovered.**
- Some of them will be optimal for cosmological measurements:
  - lensed quasars, supernovae
  - multiple-source lensing systems
- The process of finding and spectroscopically confirming objects is somewhat arduous, but we can improve this with new finding techniques.
- Convolutional neural nets
  - success in galaxy classification (Dieleman et al.)
  - initial tests on strong lens classification very promising.
- Techniques like neural nets will be critical for surveys LSST, which is even larger than DES.

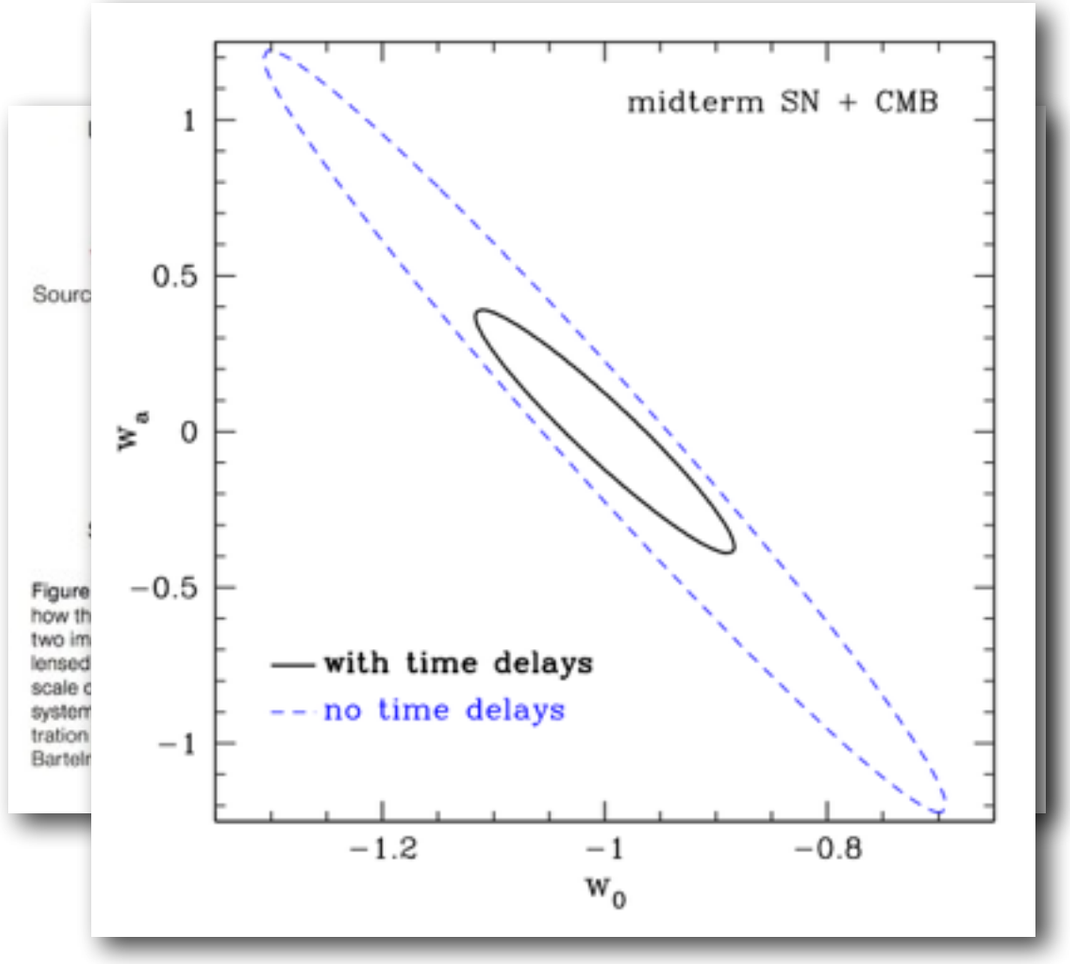


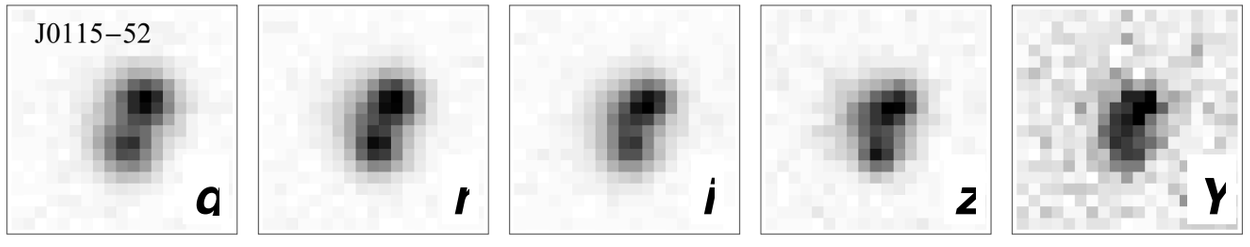


Extras

Lenses for Cosmology
Time delays

- The time delay between different light paths is proportional to the Hubble constant, H_0 (Refsdal, 1964)
- Systematics: quasar samples and mass modeling
- Complementary to CMB and SNe, improving dark energy constraints by over 50%
- STRIDES:
  STRong lensing **I**nsights into **D**ark **E**nergy **S**urvey (collaboration with external partners, led by T. Treu)

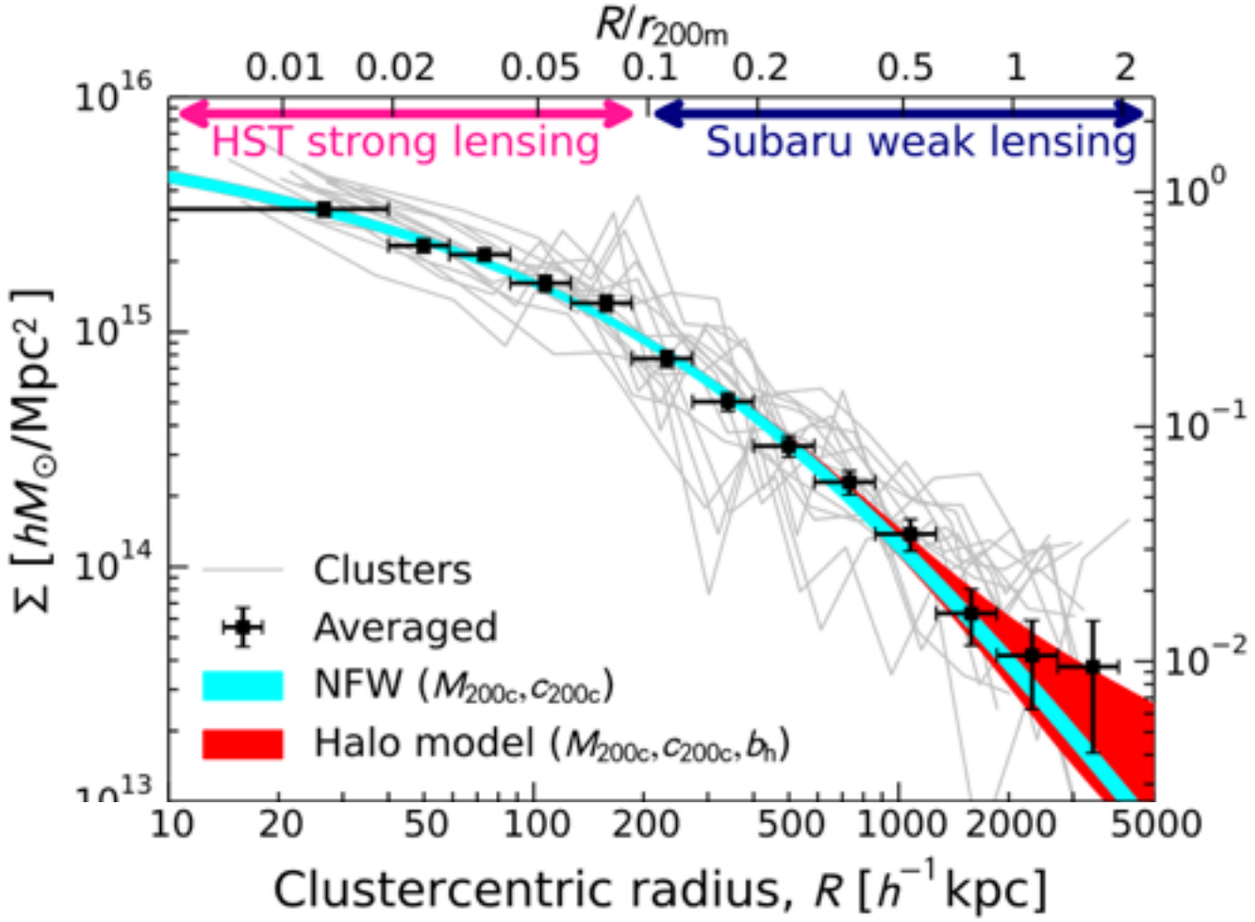




[Agnello++,2015; arXiv:1508.01203]

Lenses for Cosmology
Dark matter halo profiles

- Combining weak and strong lensing allows measurements of cluster density profiles over a large dynamic range.
- Strong and weak lensing probe inner and outer radii, respectively
- <u>16 stacked clusters</u>
  - profiles are well fit by canonical NFW model, *not* by power laws
  - concentration-mass relation shows agreement with LCDM
  - strong lensing is key for these studies.



Umetsu++2015